(2)

ANTEING UP: THE GOVERNMENT'S ROLE IN THE MICROELECTRONICS INDUSTRY

Anna Slomovic

December 16, 1988

P-7516-RGS

ANTEING UP: THE GOVERMENT'S
CHANGING ROLE IN THE MICROELECTRONICS INDUSTRY

Anna Slomovic

December 1988

The author, Anna Slomovic, is a Fellow of the RAND Graduate School. This paper was originally written for the Civil and Military Technology workshop conducted by C.R. Neu in the Spring of 1988.

CONTENTS

FIGURES

TABLES

I. INTRODUCTION

This paper is a case study of the microelectronics industry. It is an attempt to look at the role that the federal government has played, and still plays, in the development of the industry, and at the outcomes of this intervention.

The federal government's role has been important and wide-ranging. It has made investments in microelectronics research and development, supported the industry in its infancy as a first and major customer, and created a demand environment in which companies had incentives to advance the state of the art. Sometimes the government opted for high-risk high-return solutions to allow new technologies to develop. In return, the government was a beneficiary of the most advanced technology for its systems. However, as the market for microelectronics exploded, the relative position of government and other customers has changed. As companies turned to fill the ever-larger demand for electronics in the commercial marketplace, the government has found it more difficult to meet its requirements for specialized products. As a result it is once again investing in research and development directed specifically at its own applications.

For much of their history, the U.S. microelectronics manufacturers have dominated world markets. This has begun to change in recent years as Japanese manufacturers have acquired significant and growing shares of these markets. The U.S. manufacturers have asked the government to intervene in the international competition on their behalf. They have lobbied for and won passage of protective trade legislation, and have established a government-industry research and development consortium, Sematech, which is expected to help them compete in international markets. Thus the government has assumed a new role: it is no longer only a provider of a specialized market that stimulates technological innovation, but also a direct participant in the commercial sector of the industry.

This paper explores the relationship between the government and the microelectronics industry as follows. Section II is a brief history of microelectronics and the microelectronics industry. It includes a discussion of various government interventions. Section III examines the technology of integrated circuits and attempts to correlate the technological factors to the structure of the industry. This section includes an examination of the structure of the U.S. microelectronics industry and looks at the relative position of the U.S. industry vis a vis Japan and Europe. This is followed by Section IV which examines public policy towards the microelectronics industry. Finally, there is an attempt to determine

whether government intervention has made a difference. The paper concludes with an annotated bibliography.

II. MICROELECTRONICS: A HISTORICAL OVERVIEW

The history of microelectronics really began before World War II. As early as 1938 or 1939 Mervin Kelly, the research director at Bell Laboratories, knew that switching in telephone exchanges would eventually have to be done not by mechanical relays but by electronic connections if the growing volume of traffic was to be accommodated.[1] During those early days, however, such devices were only a theoretical possibility. In fact, the first solid-state amplifier built by William Shockley of Bell Labs in 1939 failed to work.[2] Electronic equipment using vacuum tubes came into use before World War II, and greatly grew in use and sophistication during the war. Widespread use of vacuum tubes, which were bulky and expensive, as well as notoriously fragile and unreliable, accentuated the need for research into alternative technologies, such as solid-state electronics.

DISCRETE DEVICES

The major breakthrough in solid-state electronics came with the invention of the point-contact transistor at Bell Labs in 1947. The development was a team effort by William Shockley, John Bardeen and Walter H. Brattain, who shared the 1956 Nobel Prize in physics for their invention. Their research was part of a larger Bell Labs research program aimed at finding new and more efficient switching devices and amplifiers for telephone communications systems.[3]

By 1952, junction transistors were commercially produced by Western Electric, the manufacturing arm of AT&T. However, these early devices were not very reliable, operated within a restricted range of temperatures and electrical frequencies, and were difficult to produce. In addition, they were made of germanium, a relatively rare and, therefore, expensive material. In the early 1950s, solid-state electronics research and development (R&D) efforts were concentrated in three areas. It was necessary to seek

---

[1]Richard C. Levin, "The Semiconductor Industry," in *Government and Technical Progress*, Richard R. Nelson, ed., Pergamon Press, New York, 1982, p. 40.

[2]Levin, op. cit., p. 40.

[3]According to several sources, there is no evidence that latent military demand played a significant role in inducing the invention of the transistor. The Bell System was a large enough customer to justify significant expenditures of R&D funds. (See, for example, Levin, op. cit., p. 58)

materials of greater purity in order to increase device reliability, to develop devices that were capable of operating under a wider range of conditions, and to find semiconductor materials other than germanium. All of these goals were accomplished during the first decade. By 1954, Texas Instruments (TI) became the first producer of a silicon transistor, and enjoyed a three-year monopoly on the device. By 1956, TI became the innovator in production of high-purity silicon for use by the entire industry.[4]

Replacement of germanium by silicon as the main microelectronics material was gradual. There were technical difficulties in purifying silicon, and germanium showed greater frequency response at room temperatures. However, the military demanded a product that was capable of operating within a wider temperature range than germanium made possible. This was a major source of demand for silicon devices. With the invention of the integrated circuits, silicon demonstrated its advantage in formation of oxide layers and deposition of metallic films, which made its use advantageous for these devices. Production of silicon devices finally overtook production of germanium devices in 1966.

The first significant R&D effort at miniaturization of solid state devices was made by the Navy in cooperation with the National Bureau of Standards. The project was known as Tinkertoy. The objectives of the project were to reduce the size of electronic circuits and to automate the process of circuit assembly. The project spent about $5 million between 1950 and 1953 (approximately $26 million in 1982 dollars).[5] It was a technical success, but was made obsolete by the time it was over by concurrently developed transistor production methods.[6]

The crowning achievement of the discrete device era, and the bridge to the era of integrated circuits, was the invention of the Planar Process at Fairchild Semiconductor in 1958. This process technology, while originally used for mass production of transistors, was ideally suited for the production of integrated circuits.

---

[4]Levin, op. cit., p. 43.

[5]The deflators used in this paper are deflators for total federal government purchases of goods and services taken from the table of implicit price deflators for gross national product, 1929-87, in the Economic Report of the President, 1988, p. 253.

[6]Levin, op. cit., p. 70.

INTEGRATED CIRCUITS

G.W.A. Dummer of the Royal Radar Establishment in Great Britain is credited with the idea that led to integrated circuits. He wrote in 1952:

> With the advent of the transistor and the work in semiconductors generally, it seems now possible to envisage electronics equipment in a solid block with no connecting wires. The block may consist of layers of insulating, conducting, rectifying and amplifying materials being connected directly by cutting out areas of the various layers.[7]

Dummer's proposal intrigued scientists worldwide, and the race for the invention of the integrated circuit was on.

Throughout the 1950s the U.S. military showed an intense interest in miniaturization of electronic devices. Several different approaches were tried. The Army Signal Corps spent $26 million (approximately $105 million in 1982 dollars) between 1957 and 1963 on the Micromodule Program, mainly at RCA. The Army's Diamond Ordnance Fuze Laboratories funded a program of in-house and contract research in "thin-film" circuits between 1957 and 1959. The Navy began its own "thin-film" circuit program in 1958. In the meantime, the Air Force pursued "molecular electronics"—development of solid-state devices that performed the function of electronic devices but did not correspond part for part to conventional circuits. The integrated circuit, as it later became known, did not fit into any of these programs.

Jack S. Kilby of Texas Instruments, working without government funding but aware of government interest, demonstrated the first working circuit composed entirely of semiconductor elements on August 28, 1958. The critical insight was that passive components could be fabricated from semiconductor material, just as active components were fabricated at that time. Although his was not a wholly integrated circuit, it was a significant advance in the state of the art. Kilby's next step was to lay out all the components on single bar of germanium, and this circuit was demonstrated on September 12, 1958. He took steps to patent the device in January 1959; the device was revealed to the public on March 6, 1959. After the demonstration of Kilby's device, Texas Instruments began dropping its other microminiature products and concentrated on moving the integrated

[7]Quoted in F. X. Ross, *The Magic Chip*, J. Messner, New York, 1984, p. 17.
[8]Levin, op. cit., pp. 70-72.
[9]Ross, op. cit., p. 21.

circuit from the laboratory to the marketplace.[9] The support from the military proved critical at this stage. Although the Air Force did not abandon its molecular electronics program, it did award a $1.15 million contract to TI to design and fabricate circuits that would perform specific functions and would be made of silicon.[10]

While Kilby's devices were fabricated by hand in the laboratory, Robert Noyce at Fairchild realized that the planar process could translate the laboratory curiosity into a commercially viable product. Noyce filed a patent for a planar integrated circuit in July 1959, and a lengthy patent dispute followed. Eventually, the dispute was resolved in favor of Noyce. The main driving force in further development of integrated circuits was miniaturization.

The advantages of miniaturization were most important to the military and the manufacturers of computers. While discrete components were quite reliable by 1960, the large number of components within a system introduced unacceptably high failure rates. In addition, many failures occurred in the interconnections between components. Integrated circuits had the potential to solve both problems.

Initially, however, integrated circuits were greeted with skepticism in the private sector. In fact, IBM, which in 1960 was the largest single private-sector customer of every major semiconductor house, opted against the use of integrated circuits in its new 360 series of computers.[11] Two government procurement decisions were responsible for moving integrated circuits into large-scale production. In 1962 NASA announced that its prototype Apollo guidance computer would use integrated circuits. Shortly thereafter, the Air Force announced the use of integrated circuits in the Minuteman II guidance package. Although considerable risk was involved in these choices of a relatively new technology, both agencies decided to opt for the high-risk high-return alternative.

In addition to providing the solution to technical problems, miniaturization was thought capable of lowering the cost of chips. Since most of the cost of fabrication occurred in wafer processing and in subsequent assembly and packaging operations, it was conjectured that increasing the number of components on a single chip would not raise the cost of the chip proportionately. This proved to be true, as will be discussed in the next section. The progress of miniaturization has moved from Medium Scale Integration (MSI, 10-100 digital logic gates per chip) in the 1960s, to Large Scale Integration (LSI, 100-1000 gates per chip) in the mid-1970s, to the Very Large Scale Integration (VLSI,

[10]Levin, op. cit., p. 72.
[11]Levin, op. cit., p. 62.

100,000-1,000,000 gates per chip) of today. Before the end of the century, we might see Ultra Large Scale Integration, involving as many as a billion components on a single chip.[12]

A wide variety of microchips has been brought to market since the mid-1960s. One of the most significant milestones in the development of ICs was the invention of the microprocessor at Intel in 1971. As ICs became more and more complex, a subsection of the industry developed that creates "semi-custom" chips, designed to fit into specific systems by performing specific functions.

As microelectronic devices came to be used in more and more sectors of the economy, the size of the market increased enormously. While the military's use of integrated circuits also grew, its share of the semiconductor market fell, as shown in Table 1.[13] Several factors, in addition to the relatively small size of the military market, have been responsible for the increasing unwillingness of commercial companies to produce chips for the military. The military requires its chips to perform under a wider range of temperature and radiation conditions than those required for commercial products. It has a very stringent and highly specific program for reliability assurance. It requires firms to be able to supply the same chips during the entire lifetime of a weapons system—the lifetime that is generally much longer than the lifetimes of commercial systems. In addition to this, dealing with the military involves much less predictable quantity fluctuations than those involved in the commercial markets.

As a result of decreased enthusiasm by commercial chip manufacturers, the military has found it increasingly difficult to stay on the leading edge of technology. This led the Department of Defense to start a high-priority program in 1979 to develop a Very High Speed Integrated Circuit (VHSIC) for military applications. The goal of the first phase of the Program was to create a fivefold improvement over the best chips available in the laboratory at that time. These goals have been met. The second phase, currently underway, involves a 20-fold improvement over Phase I.[14] The Program cost started out at approximately $200 million, and is currently approaching $1 billion.

While the VHSIC Program is not aimed at commercial markets, there is a strong possibility that techniques developed in the Program will be taken over by the participating

---

[12]John W. Wilson, et al., "Superchips: The New Frontier," *Business Week*, June 10, 1985, p. 83.

[13]Levin, op. cit., p. 60.

[14]Ken Julian, "Defense Program Pushes Microchip Frontiers," *High Technology*, May 1985, p. 49.

Table 1

GOVERNMENT PURCHASE OF SEMICONDUCTOR DEVICES, 1955-1977

Year	Total Semiconductor Shipments (millions of dollars)	Shipments to Federal Government* (millions of dollars)	Government Share of Total Shipments (percent)
1955	40	15	38
1956	90	32	36
1957	151	54	36
1958	210	81	39
1959	396	180	45
1960	542	258	48
1961	565	222	39
1962	575	223	39
1963	610	211	35
1964	676	192	28
1965	884	247	28
1966	1123	298	27
1967	1107	303	27
1968	1159	294	25
1969	1457	247	17
1970	1337	275	21
1971	1519	193	13
1972	1912	228	12
1973	3458	201	6
1974	3916	344	9
1975	3001	239	8
1976	4968	480	10
1977	4583	536	12

*Includes devices produced for Department of Defense, Atomic Energy Commission, Central Intelligency Agency, Federal Aviation Agency, and National Aeronautics and Space Administration equipment.

Source: 1952-59 data from U.S. Department of Commerce, Business and Defense Services Administration, Electronic Components: Production and Related Data, 1952-59, Washington, D.C. 1960.

1960-58 data from BDSA, "Consolidated Tabulation: Shipments of Selected Electronic Components," mimeo, Washington, D.C., annually.

1969-77 data from U.S. Department of Commerce, Bureau of Census, Current Industrial Reports, Series MA-175, "Shipments of Defense-Oriented Industries," Washington, D.C., annually.

commercial firms into their VLSI programs. The commercial potential of VHSIC-type chips is most clearly demonstrated by the fact that companies that did not choose to participate in the DoD program, or those that were dropped during the down-selections at various stages, have been actively pursuing their own VLSI programs, often along the lines similar to VHSIC but on more relaxed schedules.[15] The VHSIC Program and its potential in the commercial marketplace will be discussed in more detail below.

[15]Julian, op. cit., p. 57.

III. TECHNOLOGY AND INDUSTRY STRUCTURE

The technology content of the microelectronics industry has had a strong influence on the structure of the industry. This section briefly explores the technology of producing integrated circuits, and then examines industry structure in the United States and its role in the worldwide microelectronics markets.

IC PRODUCTION TECHNOLOGY[1]

Production of an integrated circuit (IC) begins with the design phase. After basic function definition and component layout, detailed designs are made. Several computer-aided design systems are available from various companies that help the designers fit the components into the available space. These systems are absolutely essential for the mask-design phase, where transistors and interconnections are laid out. Other computer tools are used for checking designs against logic equations, for modeling circuits and for simulation. The designs produced in this phase are fabricated into various masks. Mask fabrication, requiring several specialized optical machines, is usually carried out in a specialized mask-making center.

The basic (and highly simplified) process for producing an integrated circuit is shown in Figure 1.[2] Very pure crystalline silicon is produced in rods 3 in. to 5 in. in diameter. The rod is sawed into thin wafers which are polished and used in IC production. Each wafer accommodates several hundred identical ICs. Usually, several wafers containing the same circuit are processed in a batch. First, a thin layer of highly regular silicon is grown on the surface of the wafer and oxidized at a high temperature. This produces a layer of insulating oxide. The surface is then covered by a photosensitive material, called resist. A glass mask on which the pattern of the design has been etched, is placed on top of the wafer and irradiated with a light source. The exposed resist is then developed and removed. The oxide which remains in places not covered by the resist is then removed by an etching process. Finally, all remaining resist is removed.

---

[1]Although similar information can be found in a variety of sources, this section is based on pp. 51-58 of *The U.S. Microelectronics Industry* by Nico Hazewindus, Pergamon Press, New York, 1982.

[2]Hazewindus, op. cit., p. 52.

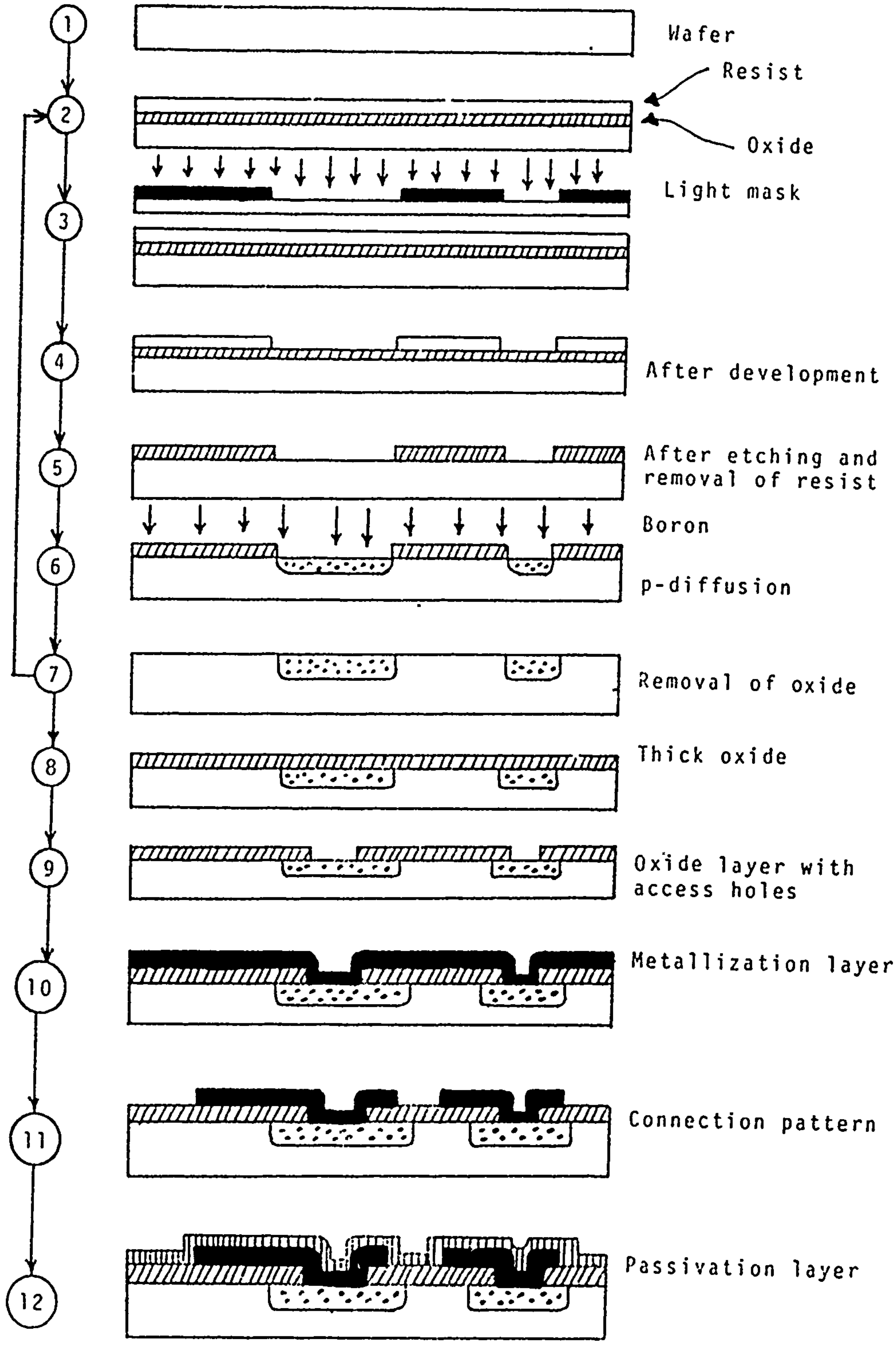

Fig. 1—Basic IC Manufacturing Process

The wafer, which now contains exposed areas of silicon, is placed in a furnace in a boron or phosphorus atmosphere. The atoms from the atmosphere diffuse into the silicon crystal lattice at high temperature, producing doped regions. Concentration profile of the dopant can be carefully controlled during the process through atmospheric dopant concentration and temperature. The remaining oxide is then removed, and the process is repeated to create other regions. Usually, a number of repetitions is necessary to complete all necessary diffusions.

After all the diffusions have been completed, a thick layer of oxide is evaporated over the entire surface. Holes are made in the oxide and a thin metal layer is evaporated on the wafer. After a desired pattern of conductors is made using lithographic techniques, undesired metal is etched away, and a protective passivating layer is applied to the entire surface.

Wafer fabrication is a laborious, and still largely manual process, although the use of computer-controlled processing and tracking is increasing. Special projectors are used in which the alignment of successive mask patterns is a major concern. Cleaning and manipulating the wafers must be performed with great care. The manufacturing takes place in "wafer fabs" of an IC house. It is here that the companies make their major capital investment in equipment and ultraclean rooms.[3]

After the wafer is fabricated, it is tested and cut into individual chips. The chips are glued to a metal frame that contains the pins of the IC package. The circuit is connected to the pins with very thin gold wires. A plastic or ceramic housing is provided around the IC. This part of the manufacturing process requires a great deal of manual work. For this reason, many merchant IC manufacturers have established assembly facilities in low-wage-rate countries. Captive manufacturers in the U.S. and Japanese manufacturers have opted for automation instead.[4]

---

[3]Class 10 clean rooms in which today's ICs are fabricated are built to very stringent specifications: no more than 10 0.5-micron particles per cubic foot of air (a human being, breathing while standing still, generates 500 particles per minute), floors isolated from the surrounding building with vibration-damping seals (tolerances are so tight that a passing truck or someone running through the building can throw mask-projection equipment out of alignment), and buildings located only in places with stable soil. The next generation of ICs may require sufficiently high cleanliness standards that humans will be precluded from being in the cleanrooms at all. [Otis Port et al., "Intel: The Next Revolution," *Business Week*, September 26, 1988, p. 77.]

[4]I have not been able to find a reasonable explanation why different choices regarding automation are made by different classes of manufacturers in the same country.

A good measure of quality in the manufacturing process is the yield of good circuits. Yield figures are closely guarded because they directly reveal profitability of a certain operation. Typical yields are illustrated in Table 2.[5]

Over the years, industry has achieved tremendous advances in technology. In fact, the number of components per integrated circuit has doubled every year in the last twenty years. (This is known as Moore's Law.) Whether this will remain true during the VLSI era and beyond is not clear. The major drivers in decreased size of ICs have been decreased size of individual cells, enlarged chip sizes and decreased line widths for conductors. Advances in silicon production technology have increased the standard diameter of wafers from 2 in. several years ago to about 4 in. today, which allows production of four times as many chips from the same set of processing steps, and allows cost to fall. One of the possible courses of research to be pursued in the next several years is creation of manufacturing techniques for making chips on 8 in. wafers, increasing productivity further.[6]

Table 2

TYPICAL YIELDS IN INTEGRATED CIRCUIT MANUFACTURING (IN PERCENT)

	Overall range of yields[a]		A typical mature product[b]		A typical new product[b]	
Process stage	Yield	Cumulative Yield	Yield	Cumulative Yield	Yield	Cumulative Yield
1. Wafer processing	75-95	75-95	80	80	70	70
2. Wafer probe: electrical test	5-90	3.8-85.5	40	32	20	14
3. Assembly: die attach and bond	80-95	3.0-81.2	90	28.8	85	11.9
4. Final electrical test	60-95	1.8-77.2	90	25.9	75	8.9

Sources: a. Integrated Circuit Engineering (1981).

b. J.P. Ferguson, cited in Finan (1975). The mature product is a standard TTL integrated circuit. The new product is an 1103 MOS integrated circuit.

[5]Levin, op. cit., p. 21.

[6]Robert Cassidy, "Can Intel's Noyce Get Sematech Rolling?" *Research and Development*, September 1988, p. 20.

One of the most significant economic features of IC production is the learning curve. Figure 2 illustrates price per bit versus time for a particular type of random-access memory (RAM) chip.[7] The figure illustrates that the price per bit drops to 68 percent of original price every time the production volume is doubled. The basic reasons for such reductions are improvements in manufacturing methods, allowing higher yields per wafer, increased size of wafers, increased number of circuits per wafer, and the transfer of labor operations from high-wage to low-wage countries or to automation.

In fact, however, the improvements that are made in ICs are not gradual. Every two or three years a new generation of ICs appears, and early entry into the market means setting the standards and acquiring large market share. The risk is that once other firms enter the market, the early entrant's advantage may erode to the point where it is not longer profitable to produce the particular circuit at all.[8]

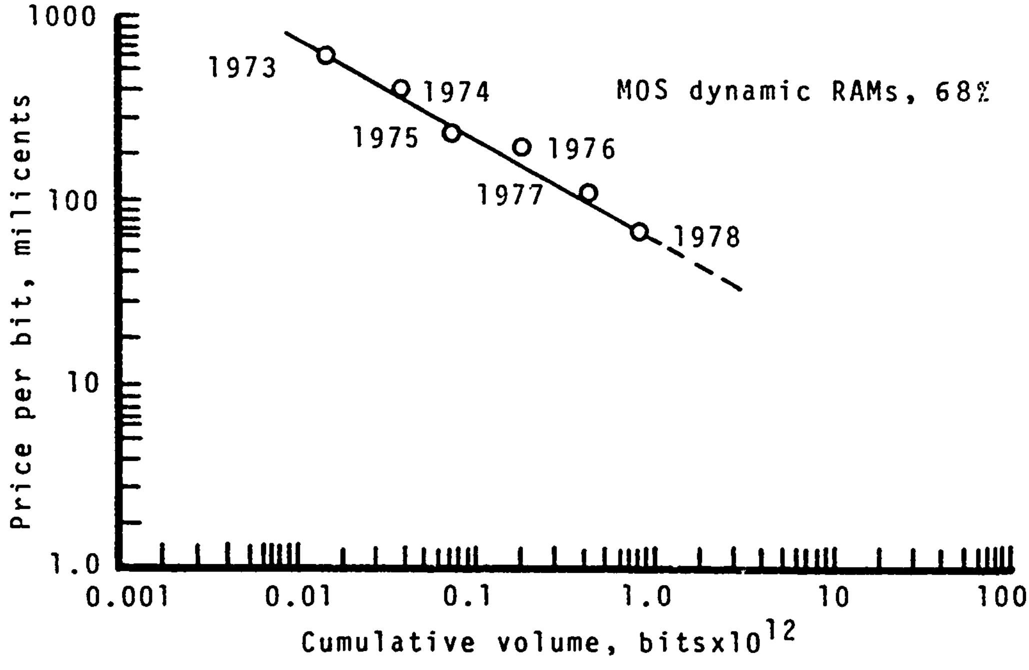

Fig. 2—Learning Curve for nMOS Dynamic RAM

---

[7]Hazewindus, op. cit., p. 13.

[8]Intel is known for its strategy of entering markets early, selling advanced chips at high prices, and withdrawing when other firms enter the market and bring down the price. I have seen indications that this is a deliberate strategy on the part of the company, and other indications that the company may be forced to abandon various markets as competition heats up and choices must be made about the markets that Intel wishes to preserve. [See, for example, Port, op. cit., p. 78.]

Several manufacturing technology advances are critical for further advances in ICs. Computer-aided design (CAD) technology has to improve in order to make VLSI design practical and cost-effective: the large and growing number of individual components has created enormous computer time requirements for design and simulation. Progress in this area has been slow. Progress has been made in the area of lithographic techniques. Manufacturers have now approached the limit of miniaturization that can be produced with visible light. X-ray lithography and electron-beam etching are promising techniques that are being developed for the future. One of the most critical areas for improvement is circuit testing. Circuits have become so complex that it has become increasingly important to design testing programs at the design stage. This is not yet common practice, however. Fully automated CAD-CAM (computer-aided design/computer-aided manufacturing) leads toward greater automation of chip production. New packaging techniques also have to be developed for VLSI circuits, since standard packages do not have enough pins to take advantage of full capabilities of these circuits.

Companies on the forefront of technological development must confront the question of whether the technologies in which they have invested are approaching ultimate physical limits. Ian Ross, president of Bell Labs, has been thinking about the limits of electronics technology, and his line of reasoning follows.[9]

> [O]ver the past decades using photolithography with visible light, we've gone from minimum line widths of 25 microns ... down to the present industry average of 2.5 microns ... approaching the wave length of light. But we're shortly going to run into the limit of the wave length of visible light and that will be a problem ... Under practical conditions [we are not likely to get below the widths of] 1 micron.
>
> The ultimate technique though, one that has already been used, is to use electron-beam lithography. And there one can predict, and indeed can demonstrate, that lines within the range one-tenth to one-hundredth micron are possible.
>
> Now when we get into that range, we are dealing with distances less than the spacing of a hundred atoms, down to ten atoms. Here, one wonders if there are not some other limitations than one's ability merely to produce small lines. And, indeed, there are.

---

[9]Quoted in Richard N. Foster's *Innovation: The Attacker's Advantage*, New York: Summit Books, 1986, pp. 72-74.

That more restrictive challenge is making operating devices that small. And here we find that there is a fundamental limitation in silicon as in other materials, and that is related to dielectric breakdown strength. Just as air breaks down under high electric field to create lightning, so too does silicon. The ultimate dielectric breakdown strength in silicon is about 100 thousand volts per centimeter. To make a useful silicon device operate at room temperature, therefore, you need to apply to it electric potentials in the neighborhood of one volt. And leaving a reasonable factor of safety, that translates into structures with dimensions no less than about a tenth of a micron. This then is more limiting than lithographic capabilities.

In the lab today, transistors with critical dimensions of 0.1 micron have been made, have been shown to operate and have been shown to perform according to theory. So possibly we may be able to achieve structures of about a tenth micron minimum dimensions with about a hundred atoms within those minimum dimensions. The could lead to a mere billion components on a square centimeter of silicon. That is not very restrictive.

Not included are the requirements to interconnect these components with current-carrying conductors that will bring adequate power to the devices. Nor does it include the minimum separation of elemental components necessary to provide adequate isolation. When these factors are taken into account, a more realistic upper limit may well be 100 million components per square centimeter.

Having dealt with minimum size of components and hence density on a chip, what can be said about future increases in the size of the chip itself? How many square centimeters per chip? ... [Wafer-scale integration may happen in the future but] for today ... I will settle for an estimate of 10 square centimeters—about an inch square—maximum obtainable chip size. This area, together with a density of 100 million components per square centimeter, would give the ultimate goal of one billion components on a chip of silicone.

Of course, every time a set of limits becomes well defined, there is an incentive to find a way to circumvent these limits. A variety of approaches is being tried with electronics. New materials, combining silicon chips with biological molecules, and superconducting circuits are some of the examples. The discussion of these technologies and their implications is beyond the scope of this paper.

INDUSTRY STRUCTURE

Richard Levin calls the semiconductor industry in the United States moderately concentrated when compared to other manufacturing industries.[10] There are two types of firms in the market: merchant producers that supply ICs on the open market and captive suppliers that produce ICs for their own internal needs (and sometimes sell the surplus on the open market). Figure 3[11] displays percentages of U.S. production by the top firms during the period from 1972 to 1984. It is important to note, however, that concentration ratios may not be very meaningful in an industry which includes merchant manufacturers which trade on world markets and captive manufacturers about which little information is available. Given the fact that many young firms enter the microelectronics market, a better measure of market dynamics is a measure of survival of any particular firm within the group of top ten

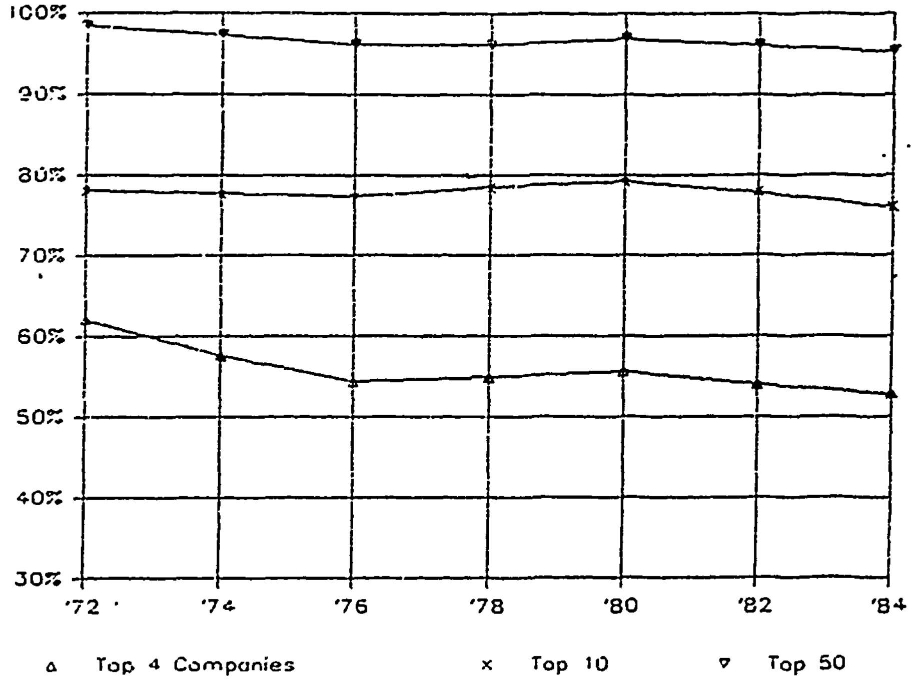

Fig. 3—U.S. Semiconductor Production by Firm Size

[10] Levin, op. cit., p. 22. Not being an economist myself, I do not know how to define moderate levels of concentration.

[11] International Resources Development Inc., *VHSIC—Military and Commercial Opportunities*, Report No. 705, Norwalk, Connecticut, July 1986, p. 73.

[12] Levin, op. cit., p. 30.

Table 3

LEADING U.S. SEMICONDUCTOR MANUFACTURERS: 1955-1980

1955 Transistors	1960 Semiconductors	1965 Semiconductors	1975 Integrated Circuits	1980 Integrated Circuits
Hughes	Texas Instruments	Texas Instruments	Texas Instruments	Texas Instruments
Transitron	Transitron	Motorola	Fairchild	National Semiconductor
Philco	Philco	Fairchild	National Semiconductor	Motorola
Sylvania	General Electric	General Instrument	Intel	Intel
Texas Instruments	RCA	General Electric	Motorola	Fairchild (Schlumberger)
General Electric	Motorola	RCA	Rockwell	Signetics (Philips)
RCA	Clevite	Sprague	General Instrument	Mostek (United Technologies)
Westinghouse	Fairchild	Philco-Ford	RCA	Advanced Micro Devices
Motorola	Hughes	Transitron	Signetics (Philips)	RCA
Clevite	Sylvania	Raytheon	American Microsystems	Harris

Sources: For 1955-1975, I.M. Macintosh, "Large Scale Integration: Intercontinental Aspects," IEEE Spectrum, June 1978, p. 54, cited in Wilson, Ashton, and Egan (1980), p. 23; for 1980, Integrated Circuit Engineering, Status 1981: A Report on the Integrated Circuit Industry, (Scottsdale, Ariz.: ICE, 1981), p. 62.

firms. Leading U.S. semiconductor manufacturers are shown in Table 3.[12] As can be seen from the figure, five of the top ten integrated circuit producers in 1975 were not among the top ten semiconductor firms ten years earlier. Once again, the picture presented by the data is not entirely accurate because the data do not include very large captive producers like IBM, AT&T and Hewlett-Packard. Furthermore, even if these firms had been included, the data do not show the degree to which the market for integrated circuits is fragmented, or that every product innovation launches a technology race from which one or two firms emerge with the major share of the market.

> The semiconductor industry offers one of the most striking examples available of "Schumpeterian competition"... where the size distribution of firms at any point in time is determined by the history of successful and unsuccessful attempts to innovate and to imitate the innovators. Thus, successful innovators like Intel and Mostek emerged rapidly from nowhere to assume a position of market leadership.[13]

[13]Levin, op. cit., p. 32.

It is interesting to look at the position of the United States firms in world markets. Table 4[14] shows the top ten merchant semiconductor firms and the top ten merchant integrated circuit manufacturing firms worldwide. Five of the top ten worldwide merchant firms are Japanese. However, when captive suppliers are included, the picture changes somewhat. Table 5 shows shares in world production by both merchant and captive U.S. manufacturers. This table shows that when captive suppliers are taken into account, the United States still holds a significant portion of the world market, although this market share has been steadily falling over the years. It is also clear that while the threat of Japanese domination has not materialized, their market share has been steadily growing.

Table 4

TOP TEN MERCHANT FIRMS WORLDWIDE

Ten Leading World Merchant Semiconductor Firms In 1985
(millions of dollars)

NEC	$1,970
Texas Instruments	1,815
Hitachi	1,750
Motorola	1,650
Toshiba	1,370
Philips*	1,010
Fujitsu	950
Intel	900
National Semiconductor	890
Matsushita	870

*Includes U.S. subsidiary, Signetics

Ten Leading World Merchant Integrated Circuit Manufacturers In 1985
(millions of dollars)

Texas Instruments	$1,730
NEC	1,400
Hitachi	1,360
Motorola	1,165
Fujitsu	900
Intel	900
National Semiconductor	840
Toshiba	790
Philips*	775
Advanced Micro Devices	610

*Includes U.S. subsidiary, Signetics

SOURCE: International Resources Development Inc., *VHSIC—Military and Commercial Opportunities*, Report No. 705, Norwalk, Connecticut, July 1986, p. 72.

[14]International Resources Development Inc., op. cit., p. 71.

Table 5

SHARES IN WORLD IC PRODUCTION (PERCENT)

	1978	1980	1982	1985
U.S. Total	68.2	73.3	69.5	62.0
Merchant	48.2	51.5	47.1	41.2
Captive	20.0	21.8	22.4	20.7
Western Europe	6.7	5.8	5.9	6.1
Japan	17.8	19.8	23.4	30.1
TOTAL	92.7	98.9	98.8	98.2

SOURCE: International Resources Development Inc., *VHSIC—Military and Commercial Opportunities*, Report No. 705, Norwalk, Connecticut, July 1986, p. 72.

One of the major market structure issues under discussion today is the very large and growing cost of entry into the market. The capital investment required to build fabrication facilities is large: a first-rate fabrication facility for mass-produced memory chips now runs about $200 million, and the price tag is expected to rise to $300 million or more by the early 1990s.[15]

> In fact, capital investment needed in this type of industry is a major concern. The capital cost is so high and the economically useful life of the equipment is so short (because of rapid improvements that come from new techniques) that a large investment is needed to obtain a turnover. (Capital investments typically amount to between 15 and 20 percent of turnover, Intel leading with 27 percent.)[16]

One of the ways in which semiconductor manufacturing firms have been acquiring access to capital is through becoming parts of larger companies. Table 6[17] shows some of the acquisition activity that has taken place during the later part of the 1970s. The effects of such acquisitions on the market are debated. Semiconductor manufacturers which are part

[15]Gary Hector, "The U.S. Chipmakers' Shaky Comeback," *Fortune*, June 20, 1988, p. 59.

[16]Hazewindus, op. cit., p. 13.

[17]Hazewindus, op. cit., p. 85.

Table 6

ACQUISITIONS IN THE U.S. SEMICONDUCTOR INDUSTRY

Company In Which Participation Is Taken	Participating Company	Country	% of Equity Owned	Year of Acquis.
AMD	Siemens	Germany	20	1977
AMI	Gould	U.S.	100	1981
AMS	General Electric	U.S.	100	1980
Analog Devices	S.O. Ohio	U.S.	20	1977
Electronic Arrays	N.E.C.	Japan	100	1978
Fairchild	Schlumberger	France/U.S.	100	1979
Interdesign	Ferranti	U.K.	100	1977
Interset	General Electric	U.S.	100	1980
Litronix	Siemens	Germany	100	1977
Mos Technology	Commodore	U.S.	100	-
MOSTEK	United Technologies	U.S.	100	1979
SEMI	GTE	U.S.	100	-
SPI	CIT-Alcatel	France	25	1981
Signetics	Philips	Netherlands	100	1975
Siliconix	Lucas	U.K.	24	1977
Solid State Scientific	VDO	Germany	25	1977
Spectronics	Honeywell	U.S.	100	-
SSS	Thomson	France	100	-
Synertek	Honeywell	U.S.	100	-
Zilog	Exxon	U.S.	50	1976

of larger firms may be able to take greater technological risks because their parent companies can absorb greater losses. On the other hand, there's fear that becoming part of a larger corporation may shift the emphasis from high technology to low-cost, low-risk production, and that will take away the major edge of American microelectronics firms over their Japanese competitors.

The fear of Japanese competition has been strong in the microelectronics industry. There are those, however, who think that Americans will excel as long they take advantage of their traditional strength: innovation. Cypress Semiconductor, a modest but prosperous startup that had $77 million in revenues last year, produces a large number of products using small, flexible fabrication lines. Cypress facilities are about one-third the size of a typical American or Japanese clean room, yet turn out many times the number of products that large facilities turn out. T. J. Rogers, head of Cypress, argues that the markets are becoming more and more fragmented, that proliferation of products will continue, and that firms like his will be a very important and highly profitable part of the industry.[18]

[18]Hector, op. cit., p. 62.

No government statistics are available on distribution of semiconductors by final markets. Richard Levin has collected data from a variety of sources for 1960 through 1979; these data are included in Table 7.[19] The data include only merchant suppliers and clearly show the changes that have taken place in the final use of microelectronics over the years. While military markets accounted for half of the microelectronics sold in the United States in 1960, this percentage has steadily declined, until the military accounted for only 10 percent in 1979. The estimate for the mid-1980s is 7 percent.[20] It was this decline that has led the military to establish the VHSIC Program in 1979.

Any time data on the microelectronics industry are presented, it is very important to note whether or not captive IC producers are included, because captive producers account for more than 20 percent of the worldwide semiconductor production by U.S.-based firms. According to Richard Levin, "IBM, the world's largest producer of integrated circuits, alone

Table 7

DISTRIBUTION OF U.S. SEMICONDUCTOR SALES BY END USE

	Percent of total semiconductor sales in year:							
End Use	1960[a]	1965[b]	1968[a]	1972[b]	1972[c]	1974[d]	1974[e]	1979[e]
Computers	30	24	35	27	28	32	29	30
Consumer Products (calculators, watches automobiles, etc.)	5	14	10	18	22	22	24	28
Industrial Products (process controls, test equipment, office and telecommunications equipment)	15	26	20	30	26	30	33	37
Military/Aerospace	50	36	35	25	24	16	14	10

Sources: a. Texas Instruments, cited in Finan (1975).

b. William D. Witter, Inc., "Basic Report on the Semiconductor Industry for 1973/74," cited in Department of Commerce (1979).

c. J.P. Ferguson Associates, cited in Finan (1975).

d. Fairchild Camera and Instrument, cited in Department of Commerce (1979).

e. Dataquest, Inc., cited in Wilson, Ashton, and Egan (1980).

---

[19] Levin, op. cit., p. 19.
[20] Julian, op. cit., p. 56.

accounts for nearly 15 percent of the U.S. total."[21] If captive production were included in Table 7, the relative importance of computers would rise markedly perhaps to as high as 40 percent of semiconductor sales.[22]

Given the recent publicity about the declining state of health in the U.S. microelectronics industry, it is instructive to read the following, as an illustration of the difference made by inclusion or exclusion of captive suppliers from statistical analysis.

> Even in microchips, perhaps the chief target of Japanese industrial policy, the U.S. has more than held its own. Although the media cite alarming market share estimates, such as a 90% Japanese share of the new generation of D-RAM production, these estimates leave out IBM, by far the world's largest producer of the chips.[23]

THE VHSIC PROGRAM

As discussed above, the military has found itself with a decreasing share of the microelectronics market in recent years. As a result, it has also found it increasingly difficult to meet its requirements for state-of-the-art products. Microcircuits became increasingly specialized in the 1970s, and characteristics of military and commercial chips diverged. Chipmaker chose to pursue the designs relevant to the much larger commercial markets, and the ICs used in military systems kept moving further from the state of the art. By the late 1970s, many of the larger defense systems suppliers were frustrated with their inability to get advanced ICs for military systems and decided to invest in their own semiconductor design and fabrication facilities. Unfortunately, the uncertainties in the defense markets made the Pentagon program managers reluctant to authorize large investments in microcircuit design during systems development phase—and the design took too long to do at later stages of programs. Still, the capabilities built up by the large defense contractors during the 1970s served as a basis for the very-high-speed integrated circuit (VHSIC) Program.

At the start of the Program, the Pentagon told potential VHSIC bidders that it preferred to award contracts to defense electronic system suppliers, rather than to IC producers. The logic behind this was that systems suppliers would be more likely to use the new chips in military systems. However, the systems houses were encouraged to team up

[21]Levin, op. cit., p. 18.
[22]Ibid.
[23] George Gilder, "How the Computer Companies Lost Their Memories," *Forbes*, June 13, 1988, pp. 79-84.

with with commercial semiconductor suppliers in order to assure that the outputs of the Program would be widely disseminated within the defense supplier community.

In 1980 the DoD selected nine contractors for Phase Zero, a group of nine-month program definition studies. Five of the nine winners were teams of military system and semiconductor firms: General Electric, teamed with Intersil; Hughes Aircraft, teamed with Signetics; Raytheon, teamed with Fairchild Semiconductor; TRW Systems, teamed with Motorola; and Westinghouse, teamed with National Semiconductor. The remaining contractors were companies whose products included both military and commercial systems: Honeywell, Rockwell International, Texas Instruments and IBM. The Phase Zero winners submitted their proposals for Phase 1 chip design and fabrication, and the field was narrowed to six Phase 1 contractors: Honeywell, Hughes, IBM, Texas Instruments, TRW and Westinghouse.

The six Phase 1 contractors were given complete freedom to select the technologies they preferred to use. As a result, a wide range of technologies was investigated. The end goals of the program, proposed by the contractors, also differed widely. IBM was the most conservative, proposing to produce a single chip; the TRW/Motorola team designed a family of 13 chips. Only IBM was able to meet the original Phase 1 schedule with its relatively modest objectives; other contractors were some months behind schedule, but all delivered working systems. Beyond having significantly higher processing power, most Phase 1 chips incorporated other novel features, such as self-test functions and redundant processors that would be engaged in case of malfunction.

In addition to its concern with improving IC performance, the DoD has also been concerned with the cost of ICs.

> [Information sharing] was done via semiannual meetings at which each contractor reported its accomplishments and its current problems. Additionally, if one contractor encountered a particularly sticky problem—say, in dry-etching metal interconnections—and a survey of others revealed similar difficulties, a special meeting was convened so each could describe the solutions it was exploring.[24]

The DoD also awarded a $15 million yield-enhancement contract to each of the Phase 1 contractors. The 32-month contracts were designed to allow each contractor to improve its own specialized fabrication process so that the yield of good chips could be increased to about 10 percent, typical of today's VLSI devices. In addition to these funds, the three

---

[24]Julian, op.cit., p. 52.

services are expected to spend about $100 million as part of their manufacturing technology improvement effort on process technologies that could be used by all VHSIC contractors.

Phase 2 was launched in 1984 and called for development by 1988 of new chips with minimum features of 0.5 microns, compared to the 1.25 micron features of the Phase 1 chips. The bidders included the six Phase 1 contractors and AT&T Technologies, teamed with Raytheon and E-Systems. As part of its concern with moving VHSIC technology into the field, the military required each Phase 1 contractor to provide the government with a VHSIC demonstration module (a brassboard system or subsystem) prior to selection of Phase 2 contractors. Phase 2, the final phase of the program, includes three contractors: IBM, Honeywell and the TRW/Motorola team. Each contractor received $60 million for a three-year effort. Phase 2 winners continued to develop the wide range of technologies they began developing in Phase 1. IBM's Federal Systems Division has announced in May 1988 that it has successfully produced the first functional chip developed under Phase 2. IBM is expected to produce four different devices during this phase.[25]

As part of the transition into sub-micron technology, the DoD spent about $60 million on Phase 3, research and development of design and fabrication techniques for Phase 2. (Phase 3 chronologically precedes Phase 2.) About 50 Phase 3 contracts were awarded in 1980-81.

Both the contractors and the government were concerned that those companies that remained in the VHSIC Program following various selections would gain a significant competitive advantage over others in the marketplace. In order to remedy the situation, the DoD sponsored a series of three-day workshops in major cities around the nation to which various contractors were invited. Nonparticipants were also encouraged to obtain CAD tools developed by VHSIC prime contractors to allow other companies to develop their own custom-designed chips

Given the perception that the U.S. military posture critically depends on the superiority of U.S. military electronics, the DoD has placed emphasis on getting VHSIC technology from the laboratory into the field. In order to reduce the time between production of new chips and their use in military systems, E. D. Maynard, the VHSIC program director, initiated a "technology insertion" program that would retrofit existing military systems with new plug-in cards, using Phase 1 chips. So many potential applications were found that the services used their own funding for studying these applications in addition to using funds available from the VHSIC Program office. This

[25]George Leopold, "Companies Boast Firsts on Chip Technology for Pentagon-Sponsored Program," *Defense News*, May 16, 1988, p. 15.

program was also envisioned as a means of diffusing VHSIC technology throughout the defense contractor community: nearly half the winners of technology insertion contracts did not participate in the Phase 1 program. Despite this, however, the movement of Phase 1 chips into the field has been slow and disappointing to the industry. Only one system, the F-111D jet, is being supplied with new cards that use VHSIC chips. This lack of penetration into the military systems has been a source of criticism of the VHSIC program. VHSIC contractors have blamed the reluctance of weapons program managers to risk the use of untried technology, exacerbated by the fact that the new chips are still expensive compared to the older ICs on the market.[26]

It is still difficult to assess whether the VHSIC Program will have a significant effect on commercial markets. A number of commercial IC manufacturers did not bid on the Program because they did not want to deal with the limitations imposed by the specialization of VHSIC chips, and by possible security restrictions. The DoD imposed restrictions on use of VHSIC technology because it is afraid that premature commercialization would allow the Soviets to duplicate the advances made in the program. Rules were set up to restrict not only the ICs themselves, but also process innovations associated with them. Now contractors that participated in the program are unhappy with the restrictions. These contractors are aware that although the military markets may be quite large in absolute terms, the commercial markets are much larger. They are concerned that the Japanese will gain a major competitive advantage while the best U.S. technology is restricted to military applications. In addition, the contractors have invested about $300 million of their own money as well as some of their best design engineers and managers into the development of VHSIC chips, probably in the expectation that they would be able to reap the benefits available beyond the military markets. Some manufacturers feel that large volumes available in commercial markets are necessary to make prices sufficiently low to induce wide-spread application of VHSIC-type technology.

At this point, the interests of the contractors and the interests of the DoD appear to be in conflict: while the DoD wants to restrict commercial applications and to disseminate the technology within the defense contractor base, the program participants want to use VHSIC technology in commercial applications and to restrict their rivals' access to the technology. This has led to some interesting maneuvering. On their own initiative, the VHSIC contractors have drafted regulations for allowable commercial use. These are being reviewed by the DoD. Whatever the restrictions, it is expected that VHSIC-type chips will find their way into the commercial systems produced by program participants.

[26]Paul Kemezis, "VHSIC Making Little Headway," *Defense Week*, April 11, 1988, p. 16.

As discussed above, DoD has taken some pains to disseminate VHSIC technology to defense contractors that did not participate in the program, which threatens the position of the contractors that did participate. IBM has taken a novel approach to protect its investment: it has combined VHSIC with its proprietary technology. The DoD cannot force IBM to share its proprietary technology, so IBM plans to market the chips within approved guidelines as standard units for military and commercial systems.

The companies that did not participate in the VHSIC Program or those that were dropped during the various phases have been funding their own programs to produce chips with performance characteristics similar to those VHSIC chips. Intel, which has refused to participate in the VHSIC Program from the beginning, is planning to unveil its new superchip, the 80486, in a few months. This chip includes over 1 million transistors and will use 1-micron technology. In 1982 General Electric funded its own Advanced Very Large Scale Integrated Circuit (A/VLSI) program, which is running about a year behind the VHSIC program schedule. Raytheon has funded its own program as well. All this is a good indication that the chips produced under the VHSIC Program are a logical step in the development of microcircuits, rather than a specialized product that will be of use only to the military.

IV. PUBLIC POLICY AND THE MICROELECTRONICS INDUSTRY

Richard C. Levin describes the impact of public policy on the semiconductor industry as follows:

> In comparison with sectors such as agriculture and aviation, the contribution of public policy in microelectronics has been modest, but nevertheless of considerable significance. Without question, the most important policy instruments influencing technical advance have been the public procurement of electronic components and systems—principally by the military services—and public support for research, development, and production engineering—principally by the military and NASA, with some contribution from the National Science Foundation and the National Bureau of Standards.[1]

Although a wide range of government policies can be examined in connection with the microelectronics industry, in this section I will examine only four: government procurement of microelectronics, government support of R&D, security regulations, and trade policy. Others, such as the effects of patents and taxation, have been less important and have been examined in Richard Levin's case study.

GOVERNMENT PROCUREMENT

While the transistor was not invented with the military in mind, the introduction of silicon and the development of integrated circuits were clearly driven by the size of latent military demand. The military was prepared to pay a high price for reliable devices to replace vacuum tubes: a 1952 study showed that 60 percent of the Navy's electronic equipment was not operating satisfactorily because of tube problems; the Air Force was concerned not only with the reliability, but size and weight of components as well. Military requirements were clear and specific: weight savings, lower power consumption, operations under adverse conditions, such as high temperatures and high levels of radiation, and low failure rates. The military was ready to be the first buyer of new products and to pay premium prices for them. The military also demanded highest quality products. As a result,

> [d]ata reported to the Defense and Business Services Administration of the Department of Commerce (1960) indicate that the average unit price for

---

[1]Levin, op. cit., pp. 9-10.

> devices sold to the military was roughly twice that received from private sector customers in middle and late 1950s.[2]

The Army's Signal Corps led service units in the purchase of semiconductors in early and mid-1950s. These devices were incorporated into communications equipment, such as radios. In 1958, when the Air Force decided to rely on semiconductors for its Minuteman missile program, demand jumped. The military supported several suppliers, at least in part because no single supplier could make deliveries at the required rate.

Texas Instruments made a conscious effort to become the first company to make a silicon transistor available to the military, and did so in 1952, as was discussed above. This breakthrough led TI to become the largest merchant supplier of semiconductor devices.[3]

Once semiconductors were well established, it became clear that there would be a great prize available to those who could create an integrated circuit device. Each service branch established its own R&D program to further miniaturization of electronics, and each program took a completely different approach. In fact, none of the approaches were those that emerged from TI and Fairchild, but the diversity of programs served as a clear indicator that the military was interested. Apparently, TI had the military exclusively in mind when Kilby developed the integrated circuit.[4]

Because of the skepticism with which integrated circuits were regarded early in the development cycle, the government was the exclusive purchaser of the devices through 1963 and most of 1964. This is illustrated in Table 8.[5] Two government procurement decisions were responsible for moving integrated circuits into production on a significant scale. The first was the 1962 NASA announcement that ICs would be used in Apollo spacecraft guidance computers. The second was the Air Force's decision to use ICs in the guidance package for the Minuteman II ICBM. Several benefits resulted from these procurements.[6]

---

[2]Levin, op. cit., p. 59.
[3]Levin, op. cit., p. 61.
[4]Levin, op. cit., p. 62.
[5]Levin, op. cit., p. 63.
[6]The points below are taken from Levin, op. cit., pp. 63-65.

Table 8

GOVERNMENT PURCHASE OF INTEGRATED CIRCUITS, 1962-1968

Year	Total Integrated Circuit Shipments (millions of dollars)	Shipments to Federal Government[a] (millions of dollars)	Government Share of Total Shipments (percent)
1962	4[b]	4[b]	100[b]
1963	16	15[b]	94[b]
1964	41	35[b]	85[b]
1965	79	57	72
1966	148	78	53
1967	228	98	43
1968	312	115	37

a. Includes circuits produced for Department of Defense, Atomic Energy Commission, Central Intelligence Agency, Federal Aviation Agency, and National Aeronautics and Space Administration.

b. Estimated by Tilton (1971).

Sources: Tilton (1971), p. 91. Total shipments data originally drawn from Electronic Industries Association, Electronic Industries Yearbook, 1969, Washington, 1969. Government share calculated by Tilton from data in BDSA, "Consolidated Tabulation: Shipments of Selected Electronic Components."

- The willingness of the government agencies to pay high prices for initial units provided incentive for the producers to enter the field, justifying the initial investment.
- The large volume of orders facilitated learning and allowed costs to fall—very important in an industry with a steep learning curve.
- Government progress payments provided cash flow and reduced technical risk.
- The military provided a very high level of user feedback which facilitated learning.
- Technology was pushed by the exacting requirements of the Air Force.
- The government's policy of second-sourcing facilitated the transfer of know-how and technological capability between companies. Far from creating ill will between companies, second sourcing was viewed as beneficial: new entrants with innovative products found advantages in second-sourcing their new products to larger established firms in order to ensure that they had customers for these products, or in acting as a second source in order to secure cash flow while they built markets for their new products.

In some cases, devices designed for the military were transferred directly into the civilian markets. In most cases, the spillover was less direct and took the form of suppliers building on their military production experience to create ICs for commercial applications. It appears that in recent years the direction of technological spill-over in many defense-related technologies, including electronics, may have reversed.[7] This is not unreasonable, given the much larger size and diversity of the civilian electronics markets, as discussed above. The loss of technological leadership and leverage that could be exercised by the military is the major reason given for establishment of the VHSIC Program.

The relationship between the government and industry has changed in other ways, too. The relationship has become more adversarial, as indicated by the government's insistence on formal product guarantees, audits, and discussions of "fraud, waste, and abuse." It is also interesting to note that the government's propensity for taking technical risks may have declined in recent years. The government has been less willing to try new technologies and new companies because such risks are perceived as a sure way to exceed budgets and attract unfavorable publicity. The lack of success in the VHSIC technology insertion program is a direct outcome of these changes.

GOVERNMENT SUPPORT FOR R&D

Although there was some early support for semiconductor R&D by the military, NASA, the National Bureau of Standards and the National Science Foundation,

> [s]ubstantially none of the major innovations in semiconductors have been a *direct* result of defense sponsored projects. Major advances in semiconductor technology have with few exceptions been developed and patented by firms or individuals without government research findings *[sic]*. Far fewer patents have resulted from defense supported R&D than from commercially funded R&D, and a far smaller proportion of those which have resulted from defense support have had any commercial use.[8]

Once the inventions were made, however, the government (and the military in particular) realized their value and supported their practical realization. As soon as the government was

[7]Congress of the United States, Office of Technology Assessment, *The Defense Technology Base: Introduction & Overview*, February 1988, p. 29.

[8]Massachusetts Institute of Technology, *The Influence of Defense Procurement and Sponsorship of Research and Development on the Development of the Civilian Electronics Industry*, NBS-GCR ETIP 78-49, June 30, 1977, p. 2.

informed of the initial Bell discoveries in July 1948, it moved to award Bell an R&D contract to expedite transistor development. As soon as batch processing of transistors and other discrete devices became possible, the Department of Defense moved to develop a large industrial manufacturing capacity in semiconductors. In 1956, the Signal Corps committed $14 million ($65 million 1982 dollars) to production refinement contracts in the transistor area. The government agreed to pay for all engineering design and development effort, while the twelve firms involved paid for capital equipment and plant space.[9]

The military's R&D programs during the time the integrated circuit was invented were described above. The most striking feature of government participation in R&D and production engineering support during the 1950s and 1960s is the flexibility with which it responded to technical innovation. It encouraged technical risk and multiple approaches, and was ready to try new products and new firms. According to Levin, this readiness to take advantage of events stemmed from the fact that the government was a major potential user of the products. Its requirements were clearly specified and the role of new products was clearly envisioned.

It is in this light that one should examine the current major government research program in the semiconductor area—the VHSIC Program. In some ways the VHSIC Program is remarkably similar to earlier government efforts: the chips that are being produced are produced strictly with the military markets in mind, a multiplicity of approaches is encouraged, and data sharing among contractors is institutionalized. If the past is any indicator of the future, however, it is possible that the major breakthroughs in technology will not come from the VHSIC Program, but from commercial manufacturers, working to meet demands of commercial markets. While VHSIC-like VLSI chips are very important to the future of industry, completely new approaches to creating more computing power are being tried by several manufacturers.[10] Based on the type of thinking expressed in the discussion of physical limits, above, it is likely that alternate approaches will become essential at some point in the future.

---

[9]Levin, op. cit., p. 67.

[10]One of the most prominent alternate approaches is reduced instruction-set computing (RISC), which allows chips to perform their tasks as much as 1,000% faster by removing infrequently used instructions from the chips' program. The increase in speed is derived from a reduced time necessary to sift through the instruction set for the correct instruction. RISC chips are more customized than ordinary ICs, and may require some users to adjust their software, but some large manufacturers are betting on this technology as an alternative to ever-denser chips produced by continuing miniaturization.

In addition to its direct involvement in research, the government has also become involved in helping the U.S. semiconductor industry do research that would increase the industry's ability to compete in world markets. A research and development consortium, Sematech, has been set up in Austin, Texas, and has been funded this year. This is a cooperative venture between industry and government, in which government contributes $100 million dollars per year and the industry members contribute $150 million per year. The industry members include IBM, Intel, DEC, AT&T, Texas Instruments, Motorola, National Semiconductor, Harris Corporation, Rockwell International, NCR, LSI Logic Corporation, Micron Technology, Advanced Micro Devices, and Hewlett-Packard. The consortium is headed by Robert Noyce, co-inventor of the integrated circuit and one of the most respected people in the industry, as Chief Executive Officer. The consortium's objectives are to significantly improve yield at wafer probe, to advance submicron processing technology, to advance wafer fabrication manufacturing equipment, and to advance X-ray lithography processing capabilities. While this venture is expected to benefit participating U.S. semiconductor manufacturers,[11] concerns about the products of the research have been expressed by both industry and government. Industry observers are worried that the government will try to direct the research because of the magnitude of its investment in the consortium. The government observers are worried that the manufacturing processes and chip designs produced will not meet military specifications. It is too early to predict how these concerns will be resolved.

SECURITY REGULATIONS

Concern with the effect of security regulations on the ability to participate in commercial markets is not new. Bell Labs was so worried that the military would classify the transistor and restrict its use to military applications that the military was not notified of the device's existence until one week before its public introduction.[12] Of course, this could only be done because the research was performed without government funding.

One of the major concerns of the firms which are participating or have participated in the VHSIC Program is the variety of security regulations which surround the chips produced in the program. Four types of regulations guide the use of VHSIC technology.[13]

---

[11] Others, including foreign manufacturers, can buy the results of Sematech research after two years.

[12] Levin, op. cit., p. 58.

[13] The points below are taken from International Resources Development Inc., op. cit., pp. 87-88.

1. National Security Classifications (NSC) can cut off all access to the technology.
2. Export licensing restriction are administered under the International Trade in Armaments Regulation (ITAR). These regulations restrict transfer of dual-use technology to non-U.S. destinations.
3. Exports are also licensed under the Export Administration Act (EAA), which covers dual-use goods and technologies not covered under ITAR, including potential dual-use technologies.
4. Contracts under the VHSIC Program contain provisions restricting the publication and dissemination of research and technical data.

These regulations are the military's way of appropriating the results of the $1 billion dollar program, of making sure that the Soviets cannot reverse-engineer the chips and decrease U.S. advantage.

The contractors view these regulations with alarm. Potential commercial spin-offs are purported to be a major reason for their participation in the VHSIC Program, and an advantageous position in the relatively small military market is no substitute. As discussed above, some of the large commercial manufacturers, such as Intel and Advanced Micro Devices, used the potential for severe security restrictions as a reason not to participate in the DoD program.

TRADE POLICY

During the first fifteen years of the microelectronics industry's existence, manufacturers were happy to sell components to the government but wanted no interference or regulation.[14] However, when the Japanese began to threaten U.S. manufacturers' markets, these companies turned to Washington for protection. Although their initial efforts where unsuccessful, they learned through their experience, and have now compiled one of the most impressive political action records in any industry. Specifically, they are responsible for the 1986 anti-dumping agreement between the United States and Japan. This agreement restricted Japanese production and sale of memory chips to such an extent that U.S. computer manufacturers are finding it extremely difficult to meet their demand even through the black market. This has resulted not only in entry of South Korean chipmakers into U.S. markets, but in the potential loss of market leadership by heretofore preeminent

[14] David B. Yoffie, "How An Industry Builds Political Advantage: Silicon Valley Goes to Capitol Hill," *Harvard Business Review*, May-June 1988, pp. 82-89.

U.S. computer makers. Only IBM, secure with its own chip production capacity, is essentially immune from the shortages.

> What about Intel, a driving force behind the U.S.-Japan [anti-dumping agreement]? On the way to a year of 51% growth and barging past the $2 billion barrier in sales, Intel is by far the fastest-growing big firm in the industry. Meanwhile, the 99 U.S. startups launched over the last five years ... constitute the fastest-growing new generation of merchant semiconductor firms in the history of the industry. So much for the U.S. chip industry's needing protection.[15]

The semiconductor industry has responded to these criticisms by arguing that the shortage did not result from the anti-dumping agreement, but rather from the delay in signing and implementing such an agreement. Japanese dumping has driven U.S. manufacturers out of the business, the argument goes, and has allowed the Japanese to create a monopoly that could manipulate supply and prices.[16] In fact, the restriction on dumping of erasable programmable read-only memory (Eprom) chips has been used as an example of successful implementation of protective trade legislation—U.S. manufacturers continue to compete successfully in the markets for these chips.

---

[15]Gilder, op. cit., pp. 79-84.

[16]No byline, "Who Caused the D-RAM Crisis?" *Forbes*, July 25, 1988, pp. 70-71.

V. THE GOVERNMENT'S CONTRIBUTION

The government, especially the military, has clearly played an important role in the development of the U.S. microelectronics industry. There are questions, however, about whether the government's involvement was necessary from the point of view of the economy as a whole, whether the special military requirements have diverted resources from uses that would have been more productive, and whether the cost to meet military requirements exceeded the return. These questions do not account for the fact that the government was spending the resources as part of its function to provide for a common defense, and assume that the government's role constitutes intervention into the civilian economy. I will address the issue of military spending for the sake of defense later in this section.

It is usually considered acceptable for the government to step in and regulate transactions within an industry if the market cannot adequately perform this function for some reason. While this sounds simple, it is not.

> Simple economic models can help focus the analyst's attention on problems of "market failure," that is, on the possibility that the market will not perform its role well in terms of generating economically justifiable technological change; however, such analyses do not carry the discussion very far, and may even mislead.[1]

> It is not so much that private expenditures will be too little in the absence of government assistance. The difficulties lie rather in the fact that the market, left to itself, is unlikely to spawn an appropriate portfolio of projects; and the added fact that all potential investors in large-scale undertakings do not have access to the results from exploratory projects. This is a more subtle view of the "anatomy of market failure." It is not a view that points clearly to particular government policies that can cope with the problems.[2]

Let us examine some possible market failures that would have justified an extended role for the government in the microelectronics industry.

---

[1]Richard R. Nelson, "Government Support of Technical Progress: Lessons from History," *Journal of Policy Analysis and Management*, Vol. 2., 1983, p. 500.

[2]Nelson, op. cit., p. 501.

One type of market failure is underinvestment in research and development. Firms face a risk of failure in R&D projects and cannot be certain of appropriating the results of their investment if they succeed. From society's viewpoint, however, it is not important whether a particular firm introduces an innovation, but only that an innovation is introduced. In fact, society may benefit from a wide diffusion of innovation while a firm may find such diffusion detrimental. Firms, therefore, have a perceived higher marginal cost for R&D investment than the social marginal cost, which leads them to invest less than socially optimal amounts of resources in R&D. It is, therefore, possible that by providing additional resources for R&D the government will move the economy toward a more optimal amount of his activity.

The government's willingness to take risks on new technology and to promote its use were significant drivers in creating a strong industrial base in microelectronics. As stated in the previous section, government-sponsored research and development did not produce the major advances in the industry. However, by allowing different approaches and technologies to be explored, the government was in effect allowing the industry to "hedge" its technological bets: the more different approaches are tried, the greater the chances that one of these approaches will prove to be "the right one." The fact that the government was not the one to make the relevant discovery is unimportant. Increasing available resources for R&D, and standing ready to buy the products resulting from it provided for the industry's growth.

Still, given the fact that the major advances were not made using government funding, it is tempting to believe that the microelectronics industry would have come to exist even without a massive infusion of government funding. At best, government intervention might have produced the industry a few years earlier than it would have happened without intervention. It is likely that the Bell system would have used transistors for switching signals. And it is likely that eventually computers and other systems would have gotten large enough to require some sort of integrated circuits to reduce failure rate and size. In this view government intervention is not justified.

The VHSIC Program is a good example of this proposition. The Program emphasizes miniaturization—the strategy pursued by commercial manufacturers without government funding. While the existence of the Program may have prompted firms to speed up their quest for ever-denser chips, the development of VHSIC-type integrated circuits is a logical extension of current technology. It is very likely that VHSIC chips possess special features, such as a wider range of acceptable operating environments and self-test

capabilities, which are more important in combat than in commercial applications. Nevertheless, the basic technology that makes them possible is technology that is being pursued without the motivation provided by military markets. In fact, proponents of greater integration between the civilian and the military industrial sectors contend that the ICs currently built for commercial applications (such as being hard-mounted on automobile engines) can already withstand the environments specified for military applications.[3]

The key unknown in this argument is the direction of causality: it is possible that certain applications were developed because the capabilities were available, just as it is possible that the capabilities were created because applications were envisioned. It is possible that the capabilities of ICs originally developed for military markets provided the incentive for firms to look for commercial applications that would allow them to create larger markets and take advantage of economies of scale. It is also possible that the size and diversity of commercial markets have driven IC capabilities, at least in recent years, and that the military can now create applications that would take advantage of these capabilities. Given the complexity and iterative nature of the innovative process, it is likely that both of these propositions are true. In this context, the question about whether the microelectronics industry would have arisen without government intervention loses its meaning.

What, then, have the U.S. taxpayers gained by spending $1 billion on the VHSIC Program? First, the VHSIC Program is probably providing the United States with several years' worth of technological lead in weapons systems over the Soviets. It may have been necessary for the military to pay for the R&D since the military was unable or unwilling to take advantage of the investment that defense systems manufacturers had made in the mid-1970s. It is important to think about the reasons why another way could not be found,[4] but this does not change the past. And while it is not possible to quantify the price of additional national security, it is certainly worth something.

Second, a benefit of the VHSIC Program might be the increased concentration of U.S. chipmakers on long-term R&D. According to the International Resource Development study,

---

[3]Jacques S. Gansler, "Integrating Civilian and Military Industry," *Issues in Science and Technology*, Vol. V, No. 1, Fall 1988, p. 70.

[4]I would need much more detailed information about the VHSIC Program and the organizational issues involved in government decision-making on the subject to be able to understand this question further.

> private firms—particularly the smaller ones—tend to emphasize R&D that is most likely to bring short-run success ... In fact, many companies defer research projects until they are fairly certain that they have a high likelihood of success: one survey of industrial research found that three-fourths of the projects begun in private laboratories had success probabilities of 80% or more, while only two percent had success estimates of less than 50% ... Even worse, a large amount of private R&D by electronic firms consists of so-called "reverse engineering"... [which] duplicates research that has already been performed and contributes nothing to scientific and technical knowledge.[5]

If the VHSIC Program corrects for this to some extent, it may be money well spent. The final evaluation of the effect of the program will have to be delayed until VLSI technology becomes more common, and the role of VHSIC in promoting this technology becomes more clear.

Another classic market failure is a situation in which the price at which the product is sold is not equal to the product's marginal cost. This type of market failure was supposedly addressed in the anti-dumping legislation. The proponents of the legislation claimed that the Japanese were selling D-RAM and Eprom chips in U.S. markets at prices below the marginal cost of the chips. As a result, U.S. manufacturers could not compete and were driven out of the D-RAM markets, leaving the Japanese with a monopoly. Once competition was eliminated, the Japanese could raise prices and extract monopoly rents. U.S. government intervention was intended to prevent the Japanese from flooding the U.S. markets, and to preserve competition—which should benefit U.S. consumers of microelectronics. The assumption here, of course, is that once the prices rose U.S. manufacturers would not be able to re-enter the markets, not an altogether unreasonable assumption in view of the high and rising capital costs involved in IC fabrication.

The problem is that "real" costs of fabrication and costs of re-entering the industry are difficult to measure. If the assumptions about these costs are correct, the anti-dumping legislation may be justified. It may also be true, however, that in the case of D-RAM chips the Japanese manufacturers were ahead of the U.S. manufacturers (e.g. because of newer and more automated plants) and were, thus, able to "legitimately" drive U.S. manufacturers out of the business—something that is not true in the case of Eprom.[6] Given the limited information available, it is difficult to judge which side of the argument has greater merit. It

---

[5]International Resources Development Inc., op. cit., p. 75.

[6]The details of this discussion can be found in Gilder, op. cit., pp. 79-84; and in "Who Caused the D-RAM Crisis?," op. cit., pp. 70-71.

is clear that U.S. computer manufacturers and other users of D-RAM chips suffered in the short run from the shortages created by the anti-dumping legislation; it is too early to judge whether the long-run effects will be different.

There is another side to this market failure, however. It is possible that U.S. government spending on R&D and production capabilities acted as a subsidy to the U.S. chipmakers. This subsidy may have allowed U.S. firms to sell ICs in world markets at prices that could not be matched by suppliers from other nations where IC production is not similarly subsidized. U.S. preeminence in the world microelectronics markets may have given U.S. firms a monopoly and allowed them to extract monopoly rents from the rest of the world.

Although U.S. manufacturers have dominated world markets during the industry's history, I do not believe that they have been in a position to extract monopoly rents because they have always competed with each other. This competition was caused by the technological facts of the industry: the learning curve and economies of scale led to brutal price wars in hope of getting large market share and maintaining profitability through volume. Users of microelectronics worldwide benefited from the abundant supply and lower prices. In fact, this is one of the great ironies of the current trade legislation: by allowing the Japanese semiconductor companies to produce fewer chips and sell them at higher prices, the U.S. government increased the profitability of these manufacturers so significantly that they are entering higher technology markets much sooner than expected. This puts an even greater strain on U.S. firms, which have traditionally dominated the high-tech end of the market.

This analysis approaches military spending from the point of view of the civilian economy. It discounts the fact that the money spent by the military was actually spent for improved military capabilities. Since the worth of military capabilities is difficult to measure, it is possible to say that the resources expended in support of military programs define the cost of such capabilities. After all, improved microelectronics did provide us with smarter and more compact weapons; greater command, control, and communications capabilities; and more accurate intelligence. In this view, the civilian benefits that resulted from military spending should be viewed as serendipitous.

There are other issues as well. It is easy to say that the military ought to take greater advantage of commercially available components because the price and reliability of these components have been tested by the markets. However, it is also possible to make the case for special military requirements resulting from a greater danger associated with malfunctions in military equipment. While an IC malfunction in a bank computer may be

costly and inconvenient, a similar malfunction in a missile guidance system may have much graver consequences. There is probably a middle ground, perhaps involving the use of components built to commercial standards and subjected to more rigorous testing. As the D-RAM shortage demonstrates, "solutions" to complicated problems may introduce more difficulties than they solve.

I believe that the influence of the military on the microelectronics industry has been largely positive. As a result, I do not believe that production of military ICs diverted resources and talent from more productive civilian uses. While products such as silicon components and integrated circuits were produced with the military's specifications in mind, these products also turned out to be extremely useful in civilian applications. I believe that there is a real potential of this happening with the VHSIC Program as well, despite security regulations. VLSI, to which VHSIC is a particular approach, is clearly the dominant technology of the immediate future. In my opinion, the DoD will not be able to stop the technology from spreading for any length of time.

There are issues that remain to be explored. I would like to understand what drives firms within the same segment of the market to automation in some cases and to low-wage countries in other cases. I would also like to understand how companies decide which markets they should enter, which markets they should abandon and how these decisions are timed and supported. It is also important to understand the events of the late 1970s that led to the establishment of the VHSIC Program. This would inovlve not only a study of the industry, but also a study of the government procurement process, and of the relationship between the government and its contractors.

ANNOTATED BIBLIOGRAPHY

-----, "Ceramics Could Hold the Key to Ultradense Chips," *Business Week*, November 14, 1988, p. 149.
Ramtron Corp. has developed a new material with electrical properties that may allow much smaller components than those that can be made with silicon. This would allow further increases in component densities beyond those that would be possible with silicon.

-----, "DARPA Assumes Management of Advanced Avionics Programs," *Aviation Week & Space Technology*, May 1, 1988, p. 111.
The responsibility for X-ray lithography has been transferred from the VHSIC program to DARPA. DARPA intends to coordinate its efforts with Sematech to ensure that there is no duplication of effort.

-----, "GaAs Circuits Key to Research at Texas Instruments Facility," *Aviation Week & Space Technology*, September 26, 1988, pp. 113-114.
Texas Instruments emphasizes monolithic gallium-arsenide integrated circuits for a number of electronic warfare applications.

-----, "Pentagon Moves to Second-Guess Commerce on Exports of Sophisticated Chips," *Inside the Pentagon*, Vol. 3, No. 24, June 12, 1987, p. 5.
DoD wants to make sure that the chips do not get diverted to the Soviet bloc nations.

-----, "Science Among the Spires," *The Economist*, September 17, 1988, pp. 97-98.
The article discusses the concept of molecular electronics—the blend of biology and physics. Although theoretical work is proceeding, it is not expected that biochips will be made before the 21st century.

-----, "Study Sees Defense Electronics Firms Benefiting From Future Arms Treaties," *Aviation Week & Space Technology*, October 24, 1988, pp. 65-67.
Electronics Industry Association study sees no decline in spending on military electronics through 1994 despite declining military budgets.

-----, "Who Caused the D-RAM Crisis?" *Forbes*, July 25, 1988, pp. 70-71.
Letters from Robert Noyce (Intel) and Jerry Sanders (Advance Micro Devices) written in response to Gilder's article entitles "The D-RAM Crisis: How the Computer Companies Lost Their Memories." They claim that the shortage of chips was caused not by the anti-dumping agreement, but by the fact that the agreement was not signed before the Japanese were able to drive U.S. manufacturers out of business and establish a monopoly. Gilder's reply is included; his article is referenced below.

-----, "With Money to Spend," *San Jose Mercury News*, December 29, 1987, p. 12B.
Congress votes funding for Sematech. There is fear in the industry that Pentagon oversight might limit the consortium and prevent it from achieving the breakthroughs it seeks.

Analytic Sciences Corporation, *The Industry Impact of the Very High Speed Integrated Circuit Program: A Preliminary Analysis*, TR-1757, Arlington, Virginia, August 15, 1980.
This study analyzes the potential impact of the VHSIC program on the microelectronics industry. Since this study was done in the earliest stages of the program, it is an interesting historical record of expectations and hypotheses of the time.

Asher, Norman J. and Leland D. Strom, *The Role of the Department of Defense in the Development of Integrated Circuits*, IDA Papar P-1271, Institute for Defense Analysis, Arlington, Virginia, May 1, 1977.
This study gives the military, and particularly the Air Force, an enormous amount of credit for the development of the IC. Contains lots of statistics on military R&D and procurement of electronics in the 1950s and '60s.

Atherton, W.A., *From Compass to Computer: A History of Electrical and Electronic Engineering*, San Francisco Press, Inc., San Francisco, California, 1984.
An interesting and well written history of electricity and its impact on civilization. Discusses electrical power, radio, and computers. Contains a chapter on miniaturization of electronics.

Auerbach, Stuart, "Semiconductor Consortium Names Chip Pioneer as Its New Chief," *Washington Post*, July 28, 1988, p. D-1.
A brief description of Sematech, the accomplishments of Noyce and Castrucci, and expectations for the consortium.

Augarten, Stan, *State of the Art: A Photographic History of the Integrated Circuit*, Ticknor & Fields, New York, 1983.
A beautiful book, with a foreword by Ray Bradbury. Color pictures include the first transistor, the first IC, and all major steps on the way to the present, as well as a GaAs chip and a Josephson junction chip.

Barna, Arpad, *VHSIC Technologies and Tradeoffs*, John Wiley & Sons, New York, 1981.
A technical book that looks at different approaches to designing VHSIC chips.

Beardsley, Tim, "Built for Speed," *Scientific American*, May 1988, pp. 26-30.
Researchers at Siemens Research and Technology Laboratories in Princeton, N.J., and at Cornell University have made transistors that are capable of record switching speed. The brief article describes the devices and discusses the importance of switching speed in applications.

Blond, David L., *The Impact of Defense Spending on the American Economy*, Presentation to the Sixteenth Annual Department of Defense Cost Analysis Symposium, Arlington, Virginia, October 4-7, 1981.
Examines the proposition that increased defense spending is inflationary and damaging to the economy, and finds that there is no evidence to support it.

Bluestone, Mimi, ed. "This Chamelion Chip Catches Costly Design Flaws," *Business Week*, November 21, 1988, p. 117.
Quicktum Systems Inc. has created a black box that tests designs of application-specific circuits during the design phase. Since each error costs time and money, IC manufacturers may be able to pay for the box by avoiding as little as one design error.

Borrus, Michael, *Reversing Attrition: A Strategic Response to the Erosion of U.S. Leadership in Microelectronics*, Berkeley: Berkeley Roundtable on International Economy, March 1985.

Referenced in the study by International Resource Development Inc. I did not have the opportunity to obtain it.

Bozeman, Barry and Albert Link, "Public Support for Private R&D: The Case of Research Tax Credit," *Journal of Policy Analysis and Management*, Vol. 4, No. 3, 1988, pp. 370-382.

Examines tax incentives and antitrust policy as they relate to R&D. The authors recommend that tax incentives would be more effective for R&D joint ventures than they would be for individual companies.

Brandt, Richard, "A Chip That May Break All Sorts of Sound Barriers," *Business Week*, October 24, 1988, p. 80.

Next Inc. is the first to use the digital signal processing (DSP) chip in personal computers for sound processing.

Cassidy, Robert, "Can Intel's Noyce Get Sematech Rolling?" *Research & Development*, September 1988, p. 20.

Robert Noyce becomes CEO of the Sematech consortium; Paul Castrucci leaves IBM to become COO.

Congress of the United States, Office of Technology Assessment, *The Defense Technology Base: Introduction & Overview*, February 1988.

Examines issues concerned with maintaining the U.S. defense technology base, such as making of technology policy within DoD, technology base funding and foreign dependence within "dual-use" civilian industries. Also includes an extensive section detailing the technology base organizations within the DoD, NASA and other federal agencies.

Cross, Michael, "Toshiba Paves the Way for Superconducting Chips," *New Scientist*, June 30, 1988, p. 49.

The Toshiba team achieves a number of breakthroughs in thin-film high-temperature superconductors that may lead to superconducting electronic devices in the next ten years.

Defense Advanced Research Projects Agency, *Strategic Computing*, Third Annual Report, February 1987.

Discusses some of the major military applications envisioned for VHSIC.

Foster, Richard N., *Innovation: The Attacker's Advantage*, Summit Books, New York, 1986.

The major idea of the book is that every technology has physical limits, and that understanding these limits is an essential element of strategic management of successful companies. Companies that have survived and flourished over the years have examined their own technologies to determine how far they are from these limits, have examined the approaches and limits of their current and potential competitors. These companies have survived by both defending their existing products (to the extent that such defense if worthwhile) and creating new products and processes that are farther away from technological limits. The author asserts that the technological forces are more important to the survival and success of firms than any other forces

associated with "good" management, and that for this reason the chief R&D manager should participate in corporate decision-making at a high level.

Gannes, Stuart, "IBM and DEC Take On the Little Guy," *Fortune*, October 10, 1988, pp. 108-114.
IBM and DEC are putting large amounts of resources into a competition in engineering workstations. These are expected to grow more powerful and to use RISC technology.

Gansler, Jacques S., "Integrating Civilian and Military Industry," *Issues in Science and Technology*, Vol. V, No. 1, Fall 1988, pp. 68-73.
This piece advocates greater integration between the civilian and the military parts of the economy. It advocates greater use of off-the-shelf components manufactured for commercial markets, greater use of design-to-cost techniques, and greater support for industries and programs with commercial and military uses.

Gilder, George, "How the Computer Companies Lost Their Memories," *Forbes*, June 13, 1988, pp. 79-84.
A strong piece in support of free markets. Considers the effects of U.S.-Japanese anti-dumping agreement on the semiconductor industry and user industries, mainly computers.

Glaberson, William, "General Electric to Sell Its Chip Unit to Harris," *New York Times*, August 16, 1988, p. D-5.
General Electric becomes the largest American company to get out of the semiconductor industry. With the purchase, Harris more than doubles its annual semiconductor sales and moves to No. 6 position in the U.S.

Gold, Philip, "The Economics of Defense: Can Firms Meet War Needs?" *Washington Times*, May 3, 1988, p. D-8.
The article is analysis of a proposition that the Pentagon should have and industrial policy. It discusses the desire of Undersecretary Costello to place greater emphasis on manufacturing and process innovation in the defense industry, and the need to find a way to convert civilian plants and production to military goods in case of war. The DoD is trying to find a balance between procuring efficiently at home and abroad, and maintaining a manufacturing base, both of which would allow U.S. to have a surge capability.

Grossblatt, Robert, "The Evolution of VHSIC," *Radio Electronics*, Vol. 58, March 1987, pp. 59-63.
A short history of VHSIC with a technological slant.

Hartland-Thundberg, Penelope, "From Guns and Butter to Guns v. Butter: The Relation Between Economics and Security in the United States," *The Washington Quarterly*, Autumn 1988, pp. 47-54.
An examination of macroeconomic issues and their connection with national security.

Hazewindus, Nico with John Tooker, *The U.S. Microelectronics Industry*, Pergamon Press, New York, 1982.
A thorough study of the industry. It contains a survey of even the more exotic technologies, and is one of the few studies that relate technological content to industry structure. The study compares U.S. industry structure with that of Japan and Western Europe. It is also looks at supporting industries as well as at the microelectronics

industry itself, something that is very seldom done. The policy analysis side, both prospective and retrospective, is rather weak, however.

Hector, Gary, "The U.S. Chipmakers' Shaky Comeback," *Fortune*, June 20, 1988, pp. 58-64.
An interesting and well-written article. The weakened dollar has allowed the U.S. chipmakers to produce many chips at or below the cost of the Japanese, and the industry is recovering. However, the following problems remain: the size of capital investment required to continue to innovate and compete in the market has significantly increased over time; Japanese have a greater emphasis on quality; companies within U.S. mistrust each other and do not co-operate for the common good. U.S. is still leading the race for innovations.

International Resources Development Inc., *VHSIC—Military and Commercial Opportunities*, Report No. 705, Norwalk, Connecticut, July 1986.
A thorough and interesting study of the international semiconductor industry and the related semiconductor manufacturing equipment industry. It includes analysis of past, present and future markets and many economic considerations.

Julian, Ken, "Defense Program Pushes Microchip Frontiers," *High Technology*, May 1985, pp. 49-57.
A brief history of the VHSIC program, including potential applications in both military and commercial markets.

Kemezis, Paul, "VHSIC Making Little Headway," *Defense Week*, April 11, 1988, p. 16.
While VHSIC chips have been demonstrated in systems, their use in operational systems is making little progress. It is felt that the reason for this is the attempt to use the new chips in retrofitting existing systems. Industry is more enthusiastic about the prospects of Phase II chips which are designed with new weapons systems in mind.

Landau, Ralph, "U.S. Economic Growth," *Scientific American*, Vol. 258, No. 6, June 1988, pp. 44-52.
The article deals with the effects of macroeconomic policies on diffusion of innovation in society.

Leopold, George, "Companies Boast Firsts on Chip Technology for Pentagon-Sponsored Program," *Defense News*, May 16, 1988, p. 15.
IBM has announced the first functional chip developed under Phase II of the VHSIC program. Westinghouse has announced the development of a computer module using VHSIC devices.

-----, "VHSIC Founder Foresees Widespread Chip Application," *Defense News*, June 6, 1988, p. 32.
Leonard Weisberg, the founder of the VHSIC Program, predicts that the U.S. will field a new generation of electronics technology up to five years sooner as a result of the DoD program. Weisberg is now at Honeywell Inc.

Levin, Richard C., "The Semiconductor Industry" in *Government and Technical Progress*, Richard R. Nelson, ed., Pergamon Press, New York, 1982, pp. 9-100.
A thorough case study of the semiconductor industry. Provides a brief description of the technology, the market structure, the character of technical progress, and an assessment of the impact of public policy on innovation and current policy issues.

Factors considered included public procurement of semiconductor devices, government support for R&D and production capability, antitrust policy, patents, public support for higher education, and tax policy.

Mackintosh, I. M., "Dominant Trends Affecting the Future Structure of the Semiconductor Industry," *The Radio and Electronics Engineer*, Vol. 43, No. 1/2, January/February 1973, pp. 149-155.
A rather techy but not terribly useful article.

Massachusetts Institute of Technology, *The Influence of Defense Procurement and Sponsorship of Research and Development on the Development of the Civilian Electronics Industry*, NBS-GCR ETIP 78-49, June 30, 1977.
An interesting study, although somewhat out of date now.

Moore, David H. and William J. Towle, *The Industry Impact of the Very High Speed Integrated Circuit Program: A Preliminary Analysis*, The Analytic Sciences Corporation, Arlington, Virginia, August 15, 1980.
The study was done during the first year of the VHSIC Program's existence and is, therefore, speculative in nature. The conclusions of the study are that the program is likely to have a major effect on the military markets, but will be far less significant for non-military markets. Lots of good economics jargon.

Mowery, David and Nathan Rosenberg, "The Influence of Market Demand Upon Innovation," *Research Policy*, Vol. 8, 1979, pp. 102-153.
This paper examines several frequently quoted studies of innovation. The studies are usually quoted as providing support to the hypothesis that the major driver in innovation is "demand pull." Upon a close examination of the studies, the authors find that the studies have serious methodological flaws, that the "demand pull" hypothesis is not supportable by the research described in the studies (and that the authors of the studies often make much more limited generalizations than those who quote their work), and that the definition of "demand" or "needs" is so vague as to encompass almost everything imaginable. They suggest that there is a very definite role for government in supporting innovation.

Nelson, Richard R., "Government Support of Technical Progress: Lessons from History," *Journal of Policy Analysis and Management*, Vol. 2., 1983, pp. 499-514.
A short piece describing the basic findings of industry studies in *Government and Technical Progress*, edited by Nelson. I heavily relied on Levin's case study of the microelectronics industry found in that volume. (See reference under Levin.)

Palisades Institute for Research Services, *VHSIC Bulletin*, New York, New York.
I have not seen this quarterly report on the status of the VHSIC program.

Pauly, David, et al., "The Great Chip Shortage," *Newsweek*, May 16, 1988, p. 49.
The 1986 agreement between U.S. and Japan that forced Japan to stop dumping chips in the U.S. is responsible for one of the worst shortages of memory chips ever.

Pine, Art, "Computer Chip Pact Backfires on U.S. Industry," *Los Angeles Times*, June 6, 1988, Part IV, p. 1ff.
Users of semiconductors complain that the anti-dumping agreement has sent chip prices so high that their products have become uncompetitive with Japanese and South Koreans products. In addition, U.S. chipmakers have not exploited the changing prices

sufficiently quickly, which has allowed South Korean chipmakers to establish a presence in U.S. markets. There is some speculation that increased prices on all chips allowed Japanese manufacturers to have sufficiently high profits to shift into production of one megabit memory chips sooner than would have been otherwise possible. While U.S. chipmakers are trying to gain new customers in Japan, U.S. users complain that they are being ill served. The pact provides for a formal review that will take place on August 2.

Pollack, Andrew, "New Era for Superconductors," *The New York Times*, October 25, 1988, p. C-1.
Experts expect that the first uses for new high-temperature superconductors will be in highly specialized microelectronics for military applications.

-----, "Sematech's Weary Hunt for a Chief," *The New York Times*, April 1, 1988, p. D-1.
Describes the difficulty of finding a chief executive for Sematech. Most companies are reluctant to let their best people go to the consortium and have offered them inducements to stay. DoD is not happy and threatens to appoint its own chief unless the problem is resolved soon.

Port, Otis, et al., "Intel: The Next Revolution," *Business Week*, September 26, 1988, pp. 74-78.
Examines the implications of Intel's upcoming microprocessor, the 80486, that has the potential to put the power of a mainframe on a single chip. Considers implications of the rival RISC technologies for Intel and of computing in the future.

Reifenberg, Anne, "Pact Will Free Sematech Funds," *Dallas Morning News*, May 11, 1988, p. D-1.
The agreement has been signed which will allow the first funds to flow from DoD to Sematech.

Ross, Frank X., *The Magic Chip: Exploring Microelectronics*, J. Messner, New York, 1984.
A basic description of what microchips are, how they are made and used. A real "gee whiz! isn't this amazing?!" flavor.

Shea, John D., "Sematech: Right Strategy, Wrong Tactics," *DefenseScience*, October 1988, p. 62.
Examines the charter of Sematech, and warns of the danger posed by Japan to U.S. manufacturing if emphasis is placed on the wrong parts of the manufacturing process.

Tirman, John, ed., *The Militarization of High Technology*, Ballinger Publishing Company, Cambridge, Massachusetts, 1984.
Contains a chapter on miniaturization of electronics. Generally a rather irrelevant book.

U.S. General Accounting Office, *GAO Assessment of DoD's Very High Speed Integrated Circuits (VHSIC) Technology Program*, GAO/NSIAD-85-37, U.S. General Accounting Office, Washington, D.C., May 8, 1985.
A thorough but nontechnical overview of the program, including the review of the original goals and their status. GAO is concerned with further expansion of the program in view of delays in the technology insertion program. It recommends that DoD concentrate on achieving goals which were set within the limits of the existing program. DoD review and response is included as an appendix.

Waldman, Peter, "Chip Industry's Sematech Consortium Picks Austin, Texas, as Research Base," *Wall Street Journal*, January 7, 1988, p. 31.
A brief description of Sematech and good ideological quotes from industry leaders.

Wiegner, Kathleen K., "Silicon Valley 1, Gallium Gulch 0," *Forbes*, January 11, 1988, pp. 270-272.
A look at the early expectations and disappointments of Gallium Arsenide chip-makers.

-----, "Take the Money and Run," *Forbes*, August 22, 1988, pp. 37-38.
Micron Technology is one of companies responsible for the anti-dumping pact, which allowed it to rebound from serious losses to record profits. Although the company is taking steps to preserve its position in D-RAM chips, there are indications that success may be short-lived.

Wilson, John W. et al, "Superchips: The New Frontier," *Business Week*, June 10, 1985, pp. 82-89.
A discussion of submicron technology and its implications. Includes a description of fully-automated facilities necessary for the manufacture of such ICs.

Yoffie, David B., "How An Industry Builds Political Advantage: Silicon Valley Goes to Capitol Hill," *Harvard Business Review*, May-June 1988, pp. 82-89.
The article discusses the political education of the semiconductor industry, from its first unsuccessful attempts to get Washington's help in counteracting Japanese competition in the 1970s to a successful trade legislation agenda of the late 1980s. The article discusses some of the lessons learned and applied by the industry in order to achieve political success.